

Causality, Memory Erasing and Delayed Choice Experiments

Y. Aharonov^{a,b}, S. Popescu^a and L. Vaidman^a

^a *School of Physics and Astronomy*

Raymond and Beverly Sackler Faculty of Exact Sciences

Tel-Aviv University, Tel-Aviv 69978 ISRAEL

^b *Physics Department*

University of South Carolina

Columbia, South Carolina 29208

Recently, Ingraham [1] suggested “a delayed-choice experiment with partial, controllable memory erasing”. We shall show that he cannot be right since his predictions contradict relativistic causality. We shall explain a subtle quantum effect which was overlooked by Ingraham.

Let us first sketch Ingraham’s argument. He considered two atoms located close to each other. The atoms have four relevant levels: the ground state $|c\rangle$ and three excited levels, $|a\rangle, |b\rangle, |b'\rangle$. The first laser pulse puts the atoms into the superposition $\frac{1}{\sqrt{2}}(|a_1c_2\rangle + |c_1a_2\rangle)$. The atom in the state $|a\rangle$ immediately

emits a photon γ and ends up in the state $|b\rangle$. Then the quantum evolution of the system is:

$$\frac{1}{\sqrt{2}}(|a_1c_2\rangle + |c_1a_2\rangle) \rightarrow \frac{1}{\sqrt{2}}(|b_1c_2\rangle|\gamma_1\rangle + |c_1b_2\rangle|\gamma_2\rangle) \quad (1)$$

We are looking for an interference between the states of the photon γ emitted from the two atoms on a distant screen. Since there is a “memory” in the atoms of which atom emitted the photon (the state $|b\rangle$), no interference pattern is expected.

Now we add a second pulse, after the first one, but before the photon γ reaches the screen. The second pulse excites the atom in the state $|b\rangle$ to the state $|b'\rangle$ which immediately decays to the ground state $|c\rangle$ and emits a photon ϕ . In the limiting case, when the wavelength of the photon ϕ is much larger than the distance between the atoms, the states ϕ_1 and ϕ_2 of the photon emitted from the two atoms are practically identical, $|\phi_1\rangle \simeq |\phi_2\rangle \equiv |\phi\rangle$. Therefore, the memory of which atom emitted the photon γ is erased. Indeed, the quantum evolution is

$$\frac{1}{\sqrt{2}}(|b_1c_2\rangle|\gamma_1\rangle + |c_1b_2\rangle|\gamma_2\rangle) \rightarrow \frac{1}{\sqrt{2}}(|b'_1c_2\rangle|\gamma_1\rangle + |c_1b'_2\rangle|\gamma_2\rangle) \rightarrow \frac{1}{\sqrt{2}}|c_1c_2\rangle|\phi\rangle(|\gamma_1\rangle + |\gamma_2\rangle) \quad (2)$$

Consequently, in the experiment with these two laser pulses we expect to see an interference pattern on the screen.

If the above analysis were correct we could send signals faster than light in the following way. Consider an experiment performed on an ensemble

of such pairs of atoms. Bob, who has to receive the signal, is prepared to measure the interference pattern on the screen. Alice, who is located near the atoms, decides to apply or not to apply the second laser pulse. Bob will see the interference pattern, only if Alice applied the second pulse. Thus, Bob will know Alice's decision with superluminal velocity.

The argument of Ingraham is based on the fact that before the second laser pulse the two states $|b_1c_2\rangle$ and $|c_1b_2\rangle$ are practically orthogonal, while after the second pulse they evolve into the states $|c_1c_2\rangle|\phi_1\rangle$ and $|c_1c_2\rangle|\phi_2\rangle$ which are practically identical since $|\phi_1\rangle$, the state of the photon emitted by the first atom is almost identical to $|\phi_2\rangle$, emitted by the second atom. This process violates the unitarity of quantum theory and, therefore, it cannot take place.

But where is the mistake? The resolution is somewhat subtle. It is true that a single atom in the state $|b'\rangle$ immediately radiates photon ϕ . However, if we put another atom in the ground state very close to the first one (such that the scalar product of the states of the photon emitted from the two locations approximately equals 1), the probability to emit the photon reduces to 1/2 [2]. Indeed, while in the symmetric state $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|b'_1c_2\rangle + |c_1b'_2\rangle)$ the atoms emit the photon ϕ immediately, in the antisymmetric state $|\Psi_-\rangle = \frac{1}{\sqrt{2}}(|b'_1c_2\rangle - |c_1b'_2\rangle)$ the atoms can not emit the photon. One can understand this phenomenon as a destructive interference between the states of the photon emitted by the two atoms in the antisymmetric state. The

correct evolution, instead of Eq. (2) is:

$$\begin{aligned} \frac{1}{\sqrt{2}}(|b'_1 c_2\rangle|\gamma_1\rangle + |c_1 b'_2\rangle|\gamma_2\rangle) &= \frac{1}{2}(|\Psi_+\rangle + |\Psi_-\rangle)|\gamma_1\rangle + (|\Psi_+\rangle - |\Psi_-\rangle)|\gamma_2\rangle \rightarrow \\ &\frac{1}{2}(|c_1 c_2\rangle|\phi\rangle + |\Psi_-\rangle)|\gamma_1\rangle + (|c_1 c_2\rangle|\phi\rangle - |\Psi_-\rangle)|\gamma_2\rangle \end{aligned} \quad (3)$$

Since the states $\frac{1}{\sqrt{2}}(|c_1 c_2\rangle|\phi\rangle + |\Psi_-\rangle)$ and $\frac{1}{\sqrt{2}}(|c_1 c_2\rangle|\phi\rangle - |\Psi_-\rangle)$ are orthogonal, there is no memory erasing. (Since the states $|\phi_1\rangle$ and $|\phi_2\rangle$ are not exactly orthogonal, the state $|\Psi_-\rangle$ is actually only a metastable state and it will finally decay emitting a photon ϕ' . However, since it can be emitted only long after the emission time of ϕ , the state $|\phi'\rangle$ is practically orthogonal to $|\phi\rangle$. Thus, after the final decay, the memory is stored in the photon state.)

One may suspect that since the photon states $|\gamma_1\rangle$ and $|\gamma_2\rangle$ are obtained by emission from the same very close atoms, similar phenomena will happen when the photon γ is emitted. This, however, is not the case: In order to be able to yield an interference pattern the wavelength of γ has to be taken smaller than the distance between the atoms and therefore the photon states $|\gamma_1\rangle$ and $|\gamma_2\rangle$ are almost orthogonal.

References

- [1] R.L. Ingraham, Phys. Rev. A **50**, 4502 (1994)
- [2] R.H. Dicke, Phys. Rev. **93**, 99 (1954).